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PHOTOGRAPHIC FILM IMAGE ENHANCEMENT

J. L. Horner

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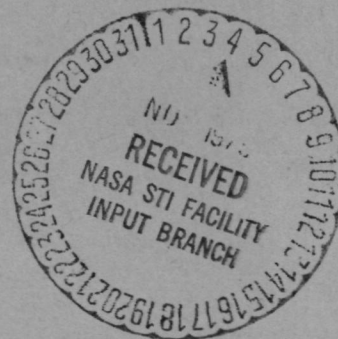
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16. Abstract <p>A series of experiments were undertaken to assess the feasibility of defogging color film by the techniques of Optical Spatial Filtering. A coherent optical processor was built using red, blue, and green laser light input and specially designed Fourier transformation lenses. An array of spatial filters was fabricated on black and white emulsion slides using the coherent optical processor. The technique was first applied to laboratory white-light fogged film (Kodak #5386 Ektachrome), and the results were successful. However, when the same technique was applied to some original Apollo X radiation-fogged color negatives, the results showed no similar restoration. Examples of each experiment are presented and possible reasons for the lack of restoration in the Apollo films are discussed.</p>					
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PREFACE

This report documents the effort to apply the technique of coherent optical spatial filtering to fogged color film. The need to develop such a technique arose out of the early Apollo flights, when it was discovered that natural radiation in outer space was inadvertently registered on the photographic films carried aboard the spacecraft. This resulted in an increase in the developed base density, causing a loss of contrast, and in the case of color film, a change in the color balance. Thus the colors shown in the developed films could not be assumed to be the colors of the actual objects photographed.

Work on this problem was begun at this installation, then the NASA Electronics Research Center, in the late 1960's, and continued after the center was assigned to the U.S. Department of Transportation as the Transportation Systems Center on July 1, 1970.

We wish to acknowledge the support of NASA, particularly Mr. Joseph P. Loftus and Mr. John W. Brinkmann NASA-Houston, and Mr. Louis W. Roberts of this Center.

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1. INTRODUCTION

This report covers the work done investigating the feasibility of applying coherent optical post-image enhancement techniques to color photographic film degraded by radiation fogging. The problem arose during the NASA Apollo program where film was carried outside of the earth's protective atmosphere for extended periods of time, and bombarded by cosmic radiation not penetrating the earth's atmosphere. This resulted in a natural fogging of the film, which in turn produced a loss of optical contrast and proper rendition of the color balance of photographed objects. Verification that radiation fogging was indeed the cause of the degradation was provided by some experiments done for NASA by Eastman Kodak Company, where unexposed film was exposed to a Colbalt 60 source.¹ A dosage of one rad. produced the same contrast loss and change in the maximum density as observed on the early Apollo flights.

Subsequently, a joint program was set up between the Phototechnology Laboratory, under Mr. John R. Brinkmann at NASA-MSC, and the Optics and Microwave Laboratory under Mr. Louis W. Roberts, of this Center, then the NASA-Electronics Research Laboratory (ERC). The goal of this effort was to study and analyze the film fogging problem, and devise a solution to it.

One obvious solution would be to put heavy lead shielding around the film. However, there is a practical limit to how far this can be carried out, as the cost of putting this enormous weight into orbit becomes excessive. Hence a search for other solutions was begun.

A considerable body of knowledge had been built up on post-image enhancement correction of certain distortions in photographic film imagery using a Fourier transform technique known as spatial filtering. This work included experiments on imagery degraded by lens out-of-focus,² linear smear caused by relative motion between camera and object during exposure,^{3,4} image blurring

caused by a turbulent atmosphere,^{5,6} and contrast loss caused by fogging.⁷ All this work had been done using black and white photographic film. In the case of color film, since degradation of color balance and loss of contrast go hand in hand, it was suggested that if a technique were available to restore contrast it might also simultaneously restore the color balance.⁸ The rest of this report is a record of the work done to test and substantiate this hypothesis.

2. THEORETICAL BASIS OF SPATIAL FILTERING

Only a brief sketch of the theoretical basis of Fourier transform spatial filtering will be attempted here, since the subject has been covered rigorously in previous reports and articles,^{9,10} and is now a text book subject.¹¹

A photograph image can be Fourier analyzed in the same analogous way that an electrical signal can. That is, it can be broken down into its component (spatial) frequencies. Mathematically this can be described as

$$I(f_x, f_y) = \frac{1}{2\pi} \iint_{-A}^A i(xy) \exp(2\pi i(f_x x + f_y y)) dx dy \quad (1)$$

x, y = spatial coordinates of image

i = image intensity (or transmittance)

f_x, f_y = spatial frequency in x or y direction

A = aperture or boundary of image

I = Fourier spectrum of image i (definition)

How does one go about performing the mathematical operations of equation (1)? There are two ways to do this; either by a digital computer programmed with the Fast Fourier Transform (FFT) and the appropriate input image digitizing hardware, or by the coherent optical computer. The latter method was used in this project.

A fundamental optical computer is shown in Figure 1. It consists of a coherent light source (laser) LA, and two lenses, L1 and L2. The photographic film transparency whose Fourier spectrum is desired is located one focal length f in front of lens L1. It can be shown that the light distribution one focal length f behind lens L1 is in fact the Fourier spectrum of the image on the input film described by equation (1) with

$$\begin{aligned} f_x &= \frac{x'}{\lambda f} \\ f_y &= \frac{y'}{\lambda f} \end{aligned} \quad (2)$$

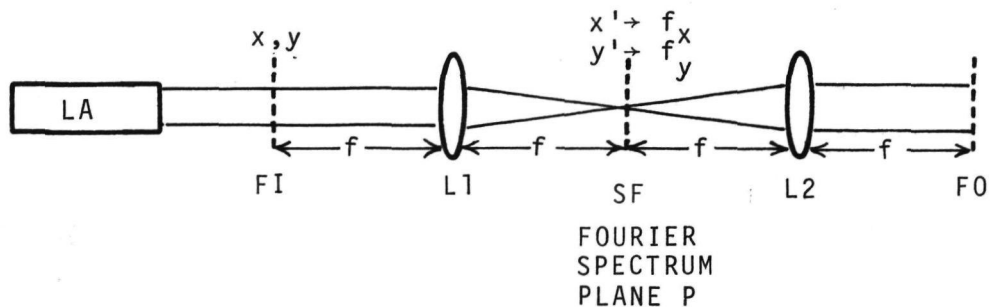


Figure 1. Fundamental Optical Computer

where x', y' = spatial coordinates in transform plane P
(one focal length behind lens L1).

λ = wavelength of the laser light

f = focal length of lens

If it is necessary to modify the spectrum, a so-called spatial filter SF is placed in the focal plane. The second lens, L2, can be thought of as taking the inverse Fourier transform of the Fourier spectrum, and forming a filtered image in the output plane FO. An unexposed film can be placed here to record the filtered image. The overall image magnification of this so-called afocal configuration is unity, and is the preferred configuration because of its convenience.

3. DEFOGGING BY SPATIAL FILTERING

When photographic film is fogged, the entire picture has its exposure increased by some amount ΔE . That is, the average exposure is increased. Looking at equation (1) it is seen that this average corresponds to the integral when $f_x = f_y = 0$, or in other words the zero frequency or DC term of the Fourier integral. Using the equation of the film sensitometry

$$D = \gamma \log E \quad (3)$$

where D is the optical density, E the exposure and γ a parameter dependent on the particular film and processing, it can readily be shown that the ratio of the AC/DC components of the Fourier spectrum decreases upon fogging. To reverse the process, after we have taken the Fourier transform of the fogged image, we must use a spatial filter which will decrease the zero frequency (DC) component relative to the AC component. This should then restore the balance between the two. The AC/DC ratio is referred to as "contrast" by photographers. In the case of color film, an additional degradation process takes place — the color balance. The exact shades and hues of the image change or fade when color film is fogged. Since the two effects — contrast and color balance — occur together it was proposed⁸ that a restoration of the former might also restore the latter. It was to this hypothesis that the effort on this project was devoted. Anticipating the results, we can say that the hypothesis is true in general, but the success of restoration varies from film to film.

For a full and complete mathematical derivation of the film fogging and restoration process by spatial filtering, including the effects of film non-linearities, reference is made to the report by D.G. Falconer of the Stanford Research Institute.¹² The report was prepared under subcontract for TSC.

4. FABRICATION OF SPATIAL FILTERS

The spatial filter required to restore the contrast of a fogged film, as explained above, must attenuate the DC frequency components relative to the AC components of the Fourier Spectrum. Physically, this would have the appearance of a gray spot on a clear background. The spatial filters were fabricated on Kodak 649F spectroscopic plates, 1"x3"x0.040" glass. This is a slow, high resolution, fine grain emulsion, well suited for this application.

The width of the gray spot on the spatial filter is determined by the diffraction limit of the optical system. Since the lens diameters are larger than the 35 mm format of the input film, it is the format aperture that must be used in the calculation.

The diffraction width of a circular aperture is

$$\theta = 1.22\lambda/d \quad (4)$$

where θ is the half angle of the first minimum, λ the wavelength of the light, and d the diameter of the aperture. To get the total linear dimension, this must be multiplied by twice the focal length, f , of the lens. For the coherent optical processor used in these experiments f is 500 mm. Since we are dealing with color film, λ will be one of three values, depending on whether the red, blue, or green laser light is illuminating the system. Taking the mid-band value of green, $\lambda = 0.528$ microns,

$$\ell = 2.f.\theta = 2.44 f\lambda/d \quad (5)$$

For an aperture of 35 mm ℓ is 18.4 microns. Falconer's work has shown that a value of twice this is optimum, when all the non-linearities are included.¹² Falconer has also shown that the ideal filter should have a transmittance vs. displacement profile of approximately an inverted, truncated, Sinc function. However, in a spot size of 36.8 microns, there is no practical way to obtain this transmittance pattern. Fortunately Falconer's work also shows

that the exact profile of the DC spot is not important for restoration. The actual filters fabricated have a Gaussian profile.

Two different arrangements were used to fabricate the spatial filters. In the first, a 25 micron pinhole was imaged onto the 649F plate by a high quality photographic copy lens. Many problems became apparent with this method. Focusing was very critical and the light source, a rheostat-controlled microscope illuminator with ground glass diffuser, was not very stable or controllable. After several attempts, this scheme was abandoned in favor of using the coherent optical processor itself to make the spatial filters, a method which proved to be very satisfactory. The laser light was stable, and its intensity was easy to adjust. To make the spatial filter, an opaque sheet with a single round circular hole was placed in the input plane of the coherent processor (FI of Figure 1), and an unexposed 649F plate was placed in the plane where the spatial filter would normally go (P of Figure 1). The size of the spot filter could be changed by changing the size of the hole in the opaque input sheet. A Joyce-Loebell microdensitometer was used to scan the spatial filter to determine its maximum density and width between half-density points. Several filters were fabricated with varying distributions of these two parameters. A typical spatial filter and its density vs. displacement plot is shown in Figure 2.

The maximum density required of the spatial filter to optimally defog a film depends directly on the severity of fogging on the film. If upon fogging a film has changed its average density by an amount ΔD , then the spatial filter gray spot should have a maximum density of ΔD at its center. This is derived rigorously in Chapter V of Falconer's report.¹²

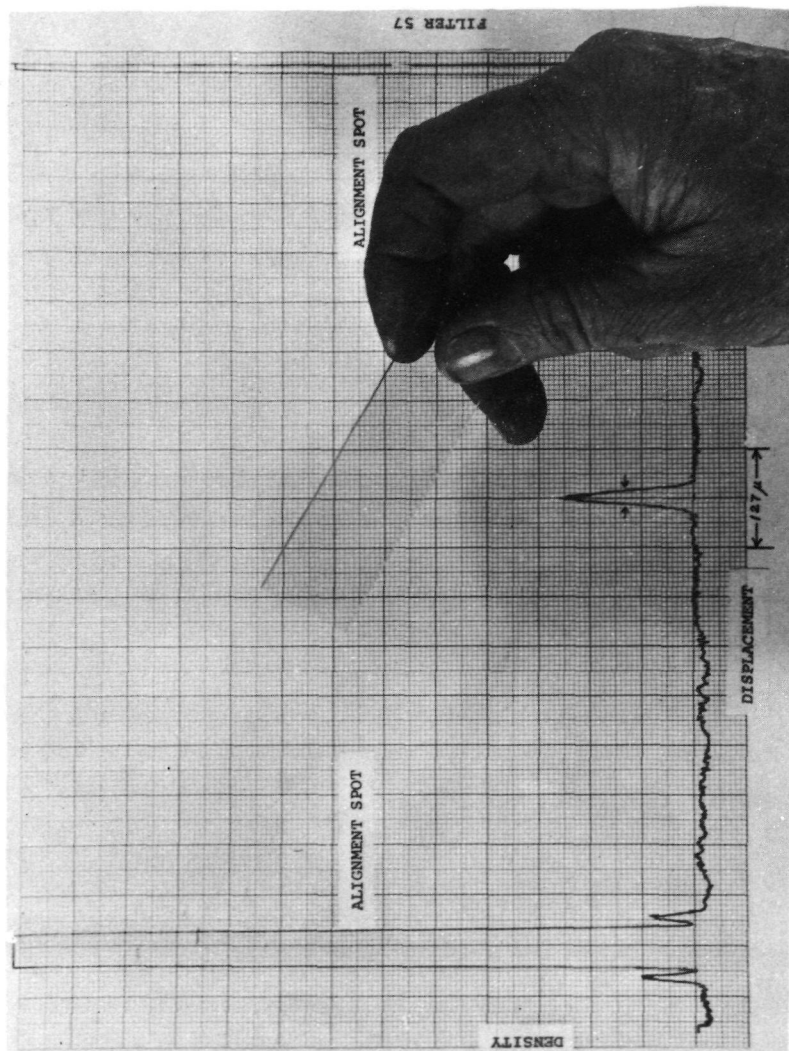


Figure 2. D vs. X Plot, Typical Spatial Filter

5. COHERENT OPTICAL PROSESSOR

The actual Coherent Optical Processor used in these restoration experiments is shown diagrammatically in Figure 3, and photographically in Figure 4. The components are the lasers (LA1, LA2) mirrors (M1, M2), beam stop (S1), beam splitter (B), variable density wedge (W), main shutter (S2), lens-pinhole spatial filter (LP), collimation lens (L1), Radiometer/Photometer (R), input stage (FI), first Fourier transform lens (L2), spatial filter stage (SF), second Fourier transform lens (L3), and output stage (FO). An auxiliary sub-system not shown in this diagram, the coherent optical noise suppressor (CONS), will be discussed separately in an appendix. Each individual component will be discussed in the order of the above list.

5.1 LASERS (LA1, LA2)

Because the fogged film is color film the coherent optical source must include red, green, and blue light. A helium-cadmium laser (Spectra Physics Model 185) supplies the blue light (4416\AA), and has a maximum power output of 50 mw. A krypton-argon laser (Coherent Radiation Laboratory Model 52G) supplies the red (6471\AA at 400 mw) and green (5309\AA at 60 mw) light. Since only one of these is available at a time, the exposure must be made in sequence - red, green and blue. If three lasers were available, the exposure would be made all at once. The exact wavelengths of the lines chosen does not seem to be critical, probably because the peaks in color film are fairly broad. It is important that the output of the lasers be stable in intensity. In this connection some problems have been experienced with the red/green laser, even though the laser does have a built-in feedback control system for regulating the light output. After about 100 hours the plasma tube failed, and the unit had to be returned to Coherent Radiation for replacement. At this time they were asked to check and repair the output control circuit. However, when the laser was returned, variations of about 5% were still present in the output light.

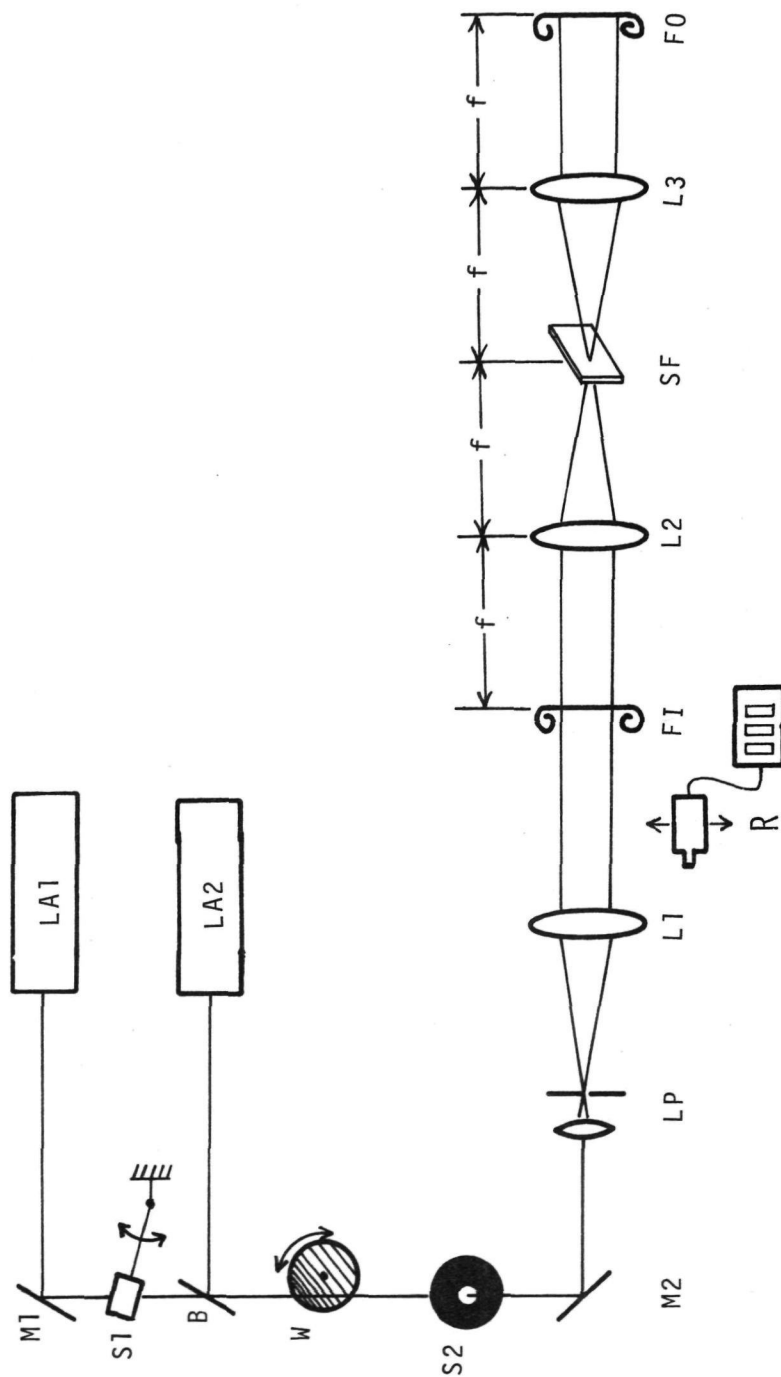
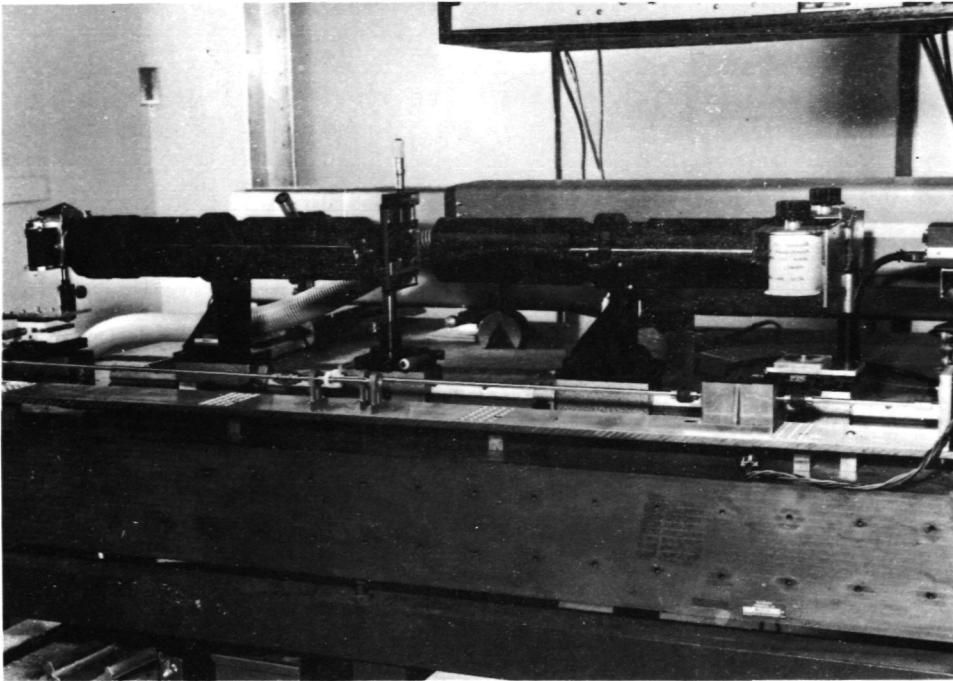
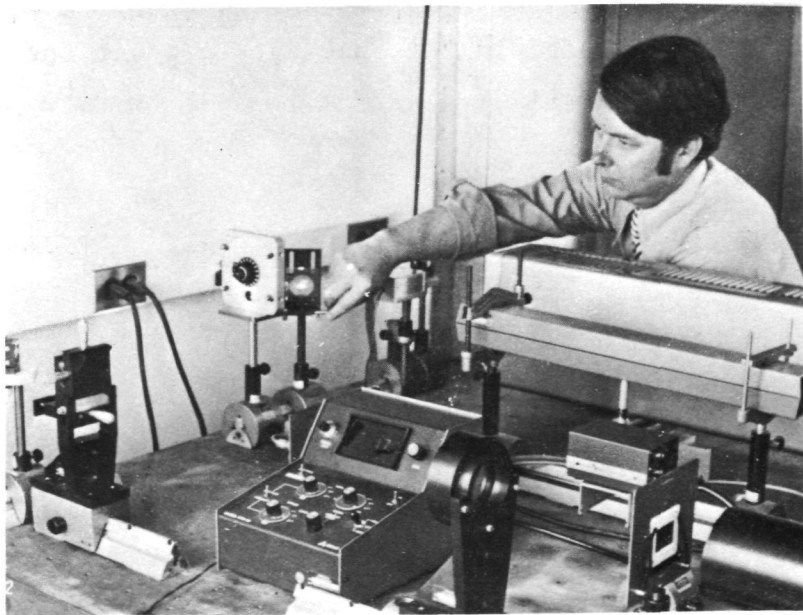


Figure 3. Schematic Diagram, Coherent Optical Processor



Overall View



End View

Figure 4. Photographs, Coherent Optical Processor

This makes operation of the optical processor a little more tedious in that the output power must be monitored and set immediately prior to exposure.

The output power of the lasers is an important consideration. Too little power results in unduly long exposures of the output film, possibly to the point of reciprocity failure. Too much power can physically burn the emulsion on the spatial filter, since in the Fourier transform plane nearly all the laser energy is focused down to a small spot. The power levels quoted above result in output exposures of 0.5 to 1.0 seconds, with no evidence of damage to the spatial filters.

An important accessory to the Coherent Radiation laser is the control system for the water cooling system. The water must be kept flowing ten minutes (minimum) after the laser is shut off. A clock timer circuit was built to handle this automatically. It is fail-safe in the sense that, if the power is momentarily interrupted during the shut-down period, the timer and the solenoid water valve it controls automatically come back on. A running time meter is also included in this package to count the cumulative hours of laser operation.

5.2 MIRRORS (M1 AND M2)

These 100% reflecting front surface mirrors are used simply to fold the beam around the optical bench.

5.3 BEAM STOP (S1)

This component, made from a 110 VAC relay, serves to block out the blue laser light when the red/green laser is being used. It is mainly for convenience, since it is operated remotely from the front edge of the optical bench.

5.4 BEAM SPLITTER (B)

This partially silvered optical flat serves to combine the output of the two separate lasers into one collinear beam. It

transmits 87% of the blue laser light, and reflects 31% of the light of the red/green laser light.*

5.5 VARIABLE DENSITY WEDGE (W)

This continuously variable optical density wheel (similar to the JODON #VBA-200) allows the light in the composite laser beam to be finely adjusted for the desired intensity.

5.6 MAIN SHUTTER (S2)

This electronically controlled, solenoid shutter (JODON #ES-6) controls the exposure of the output (restored) film. At first a photographic type shutter was used, but it was not repeatable and could not be set accurately enough; the detents only allowed accurate increments of one f stop. The electronic shutter circuit, designed and built at TSC, uses a solid-state integrated circuit (Signetics #555) timing element. The exposure time, which is continuously variable, is set from the front panel of the unit by a ten turn potentiometer. The shutter control circuit is an integral part of CONS sub-system and will be discussed later. Switches on the control panel enable the shutter to be opened indefinitely for adjustment, or used independently of the CONS system.

5.7 LENS-PINHOLE SPATIAL FILTER (LP)

This is included to expand the narrow beam from the laser, and at the same time to "clean up" the beam — i.e., make the intensity approximately uniform across the beam. A microscope objective lens (40x) focuses the beam down to a tiny spot on which a small (2 micron) pinhole is centered. Its operation is explainable using the Fourier transform concepts discussed above. The pinhole acts as a spatial filter allowing only zero frequency or

* Due to the variation in reflectivity with wavelength of the mirror across the visible spectrum these do not total 100%. The measurement was made on a Hitachi Recording Spectrophotometer.

DC components through, resulting in a uniformly diverging beam. Since the adjustments are quite critical, the pinhole is adjusted with two micrometer screws. This unit was supplied with the Fourier transform lens package.¹²

5.8 COLLIMATION LENS (L1)

This lens receives the divergent wavefront from the lens-pinhole spatial filter and renders the rays parallel. Its focal length is 23 inches. It was supplied by SORL.

5.9 RADIOMETER/PHOTOMETER (R)

This is a E.G.&G #575 unit with digital readout. It has an absolute calibration of 5% and a 1% repeatability. The light-sensitive head, containing a silicon photovoltaic photocell, is mounted on a sliding rail so that it can be quickly inserted in the expanded, collimated laser beam for a reading just before exposure. This is very important to insure the correct laser light intensity and thus the proper color balance. The instrument was used in the radiometric mode, giving a reading in units of watts/cm².

5.10 INPUT STAGE (FI)

This unit holds the fogged input film. The foundation is a micrometer adjustable translation table (Ardel Kimematic #T-100), which is part of the CONS system. On top of this is mounted a specially constructed teflon lined film holder for the Apollo 70 mm fogged input film. The unit has manually operated feed and take-up reels, and a central clear aperture of 35x65 mm.

5.11 FOURIER TRANSFORM LENSES (L2, L3)

This is the heart of the coherent optical processing system. While a good quality photographic lens can be used to demonstrate the transform-taking abilities of a lens, the design of a photographic lens is quite different from one intended for Fourier transformations. The chief design requirement is that the lens be tel-

eccentric on both the object side and image side of the lens: if the aperture stop is in the focal plane on one side of lens, then the exit pupil is at infinity on the other side of the lens and the principal rays will be parallel to the axis.

Such lenses are now off-the-shelf items for optical systems working at a single wavelength. However, since this film restoration project involved color film, the Fourier lenses had to be capable of working over the visible spectrum at the red, green, and blue laser wavelengths. Such a lens is not available off-the-shelf, so bids were solicited on an optical system consisting of two Fourier transform lenses, a collimation lens, and a lens-pin-hole spatial filter. A compromise between cost and the state-of-the-art of Fourier transform lens design resulted in the following requirements for the lenses:

All specifications must be met, or exceeded, for wavelengths of between 4200 \AA and 6400 \AA .

1. Must work with standard 35 mm film size format, input and output.
2. Unity overall magnification.
3. Must include mounting hardware for Ealing triangular optical rail, (e.g. #24-1034) with optical axis 23 cm above optical bench surface.
4. Overall length, input to output plane (excluding collimator) not to exceed 1.25 meters.
5. Broadband AR coatings on all optical surfaces.
6. Resolution in output plane of 50 line pr./mm (half-intensity point) over entire format with coherent light.
7. Power spectrum accuracy in Fourier transform plane for simple input object apertures 3% over entire format.
8. Minimum focal length: 500 mm.

9. Good cosmetic quality: glass quality and polishing techniques sufficient to guarantee no visible diffraction noise, either from speckle or descreet point imperfections.
10. Refocusing allowed only on input and output planes; lens position and Fourier transform plane to remain stationary.

Most of these requirements are self-explanatory. The fifth requirement, AR coatings, is to minimize residual interference patterns produced by the highly coherent light from the lasers. These show up as bull's-eye and bar patterns on the output image, plane FO. With the noise suppression system (CONS) to be described later, this problem is largely eliminated. The focal length, the eighth requirement, is an important consideration. The size of the DC diffraction spot, which must be exactly lined up with the attenuating spot on the spatial filter, is directly proportional to the focal length as shown in equation (2). The larger the DC spot, the easier it is to fabricate and align the spatial filter, and to measure its transmission properties with the microdensitometer. The upper limit on the focal length of the Fourier lenses is a practical one; the longer the focal length, the more spread out the system becomes, making it cumbersome to use and adjust. A focal length of 500 mm is a reasonable compromise between these two conflicting requirements.

The resolution was specified as 50 lines/mm (requirement 6). This is a compromise, also, between the desire of making a high resolution system, and what is possible with state-of-the-art Fourier transform lens design. The contract for the lenses was awarded to SORL,¹² the low bidder. After the lenses were received at TSC, resolution tests were made using a Sayce target containing spatial frequencies between 5 and 100 lines/mm. It was found that the optimum position along the optical axis for the output film was slightly different for each different color; it changed by 2.24 mm between red and green. The limit of resolution was judged to be the point where the contrast on the Sayce target image went to zero,

judged visually through a microscope. The resolution of the individual colors, when the position of the output film was optimized, was 80 lines/mm. However, it was felt that to have to re-adjust the output film plane between each different laser color would be extremely cumbersome. Consequently, a compromise position of the output film plane was determined that would make the resolution of all three about equal. Such a position was determined by trial and error. At that position, the resolution was 33 lines/mm for the blue and green, and 30 line/mm for the red. This resolution, although not up to specification 6, is adequate for the type of images processed during this project; they tend to be of relative low spatial frequency scenes. It should be pointed out that when requirement 10 is considered along with requirement 6, the manufacturer did fulfill the contractual agreement. The tenth requirement was added because it was determined that without it, the lens designer faced a physically impossible task. Each lens, L1 and L2, consists of eight elements. Considering this amount of glass and air-glass interfaces, the output plane is remarkably free of the cosmetic diffraction noise that is always in attendance with highly coherent laser light.

5.12 SPATIAL FILTER STAGE (SF)

It is necessary, and highly critical, to align the central spot of the spatial filter on the central spot of the input film's Fourier spectrum. Both are less than 50 microns in extent. Therefore, two micrometer adjustable translation tables were fastened together to make this stage: an Ardel Kinematic T-102 for the horizontal adjustment and a TT-102 with a central clear aperture for the vertical adjustment. The spatial filter is held onto the latter by a specially machined jig which accurately indexes the spatial filter while at the same time making it easy to change spatial filters quickly.

5.13 OUTPUT STAGE (FO)

A Nikon F camera body is used to hold and advance the unex-

posed output film which records the restored output image. The lens has been removed from the camera, as a focused image is presented by the Fourier transform lenses, L1 and L2. The camera is mounted on a micrometer adjustable translation table, oriented in a horizontal plane, to allow fine focusing by moving the output film along the optical (z) axis.

5.14 CONS SYSTEM

The purpose of the coherent optical noise suppression system (CONS) is to reduce the collection of unwanted diffracted light caused by bubbles, dust and dirt particles and striae in the glass of the optical elements of the system. The basic idea is to move the input and output film in unison; the optical noise remains stationary while the image moves through it. The net effect, during the half second or so exposure of the output film, is to average out the noise patterns. The CONS system has been found to be very effective. A full description of the CONS system, together with an analysis and pictures of its effectiveness, has been published,¹³ and is included in this report as an appendix.

6. METHODOLOGY

Before the optical processor can be used in film restoration experiments, it is necessary to color balance the laser light mix so that the optical processor itself does not distort the very color balance it is restoring to the film. A similar procedure must be followed in printing the developed restored color film, which is done on a Chromega enlarger at TSC. Stated another way, there are three things that determine the color balance on a print made from a spatially filtered restored film: 1) the color mix of the red, blue, and green laser light entering the optical processor; 2) the spatial filter; and 3) the color mix of the magenta, cyan, and yellow light in the enlarger. In order to allow the spatial filter to perform its defogging operation, it was necessary to color balance the printing process, and the optical processor in its non-filtering mode. To accomplish this, a test target was made on Kodak #5386 positive Ektachrome reversal film. It consisted of a patch of Kodak standard magenta, cyan, and yellow tablets, a neutral density step wedge and a "Shirley" (female model). At the same time a series of intentionally fogged frames of the test target were made. Fogged positives of 3%, 6%, 12%, 25%, and 50% were made by a double exposure technique. The test target was exposed for a time T . The test target was then removed and a white card substituted in its place. A second exposure was made for a time $n \cdot T$, where n was 0.03, 0.06, ..., 0.5, a separate frame being made for each one. The film was sent to a Kodak processing laboratory* for development. This was found necessary to insure uniformity and repeatability in the film processing. The fogged frames were later used in spatial filtering defogging experiments to assess the capability of restoration of color balance by spatial filtering under carefully controlled conditions, prior to attempts to defog the actual fogged Apollo film. The unfogged test target frame was used to adjust the color balance of the laser light mix

*Kodak Processing Laboratory, 16-31 Route 208, Fair Lawn, New Jersey 07410.

in the optical processor and the color mix of the Chromega enlarger used in printing. The unfogged test target was placed in the input of the optical processor, and with no spatial filter present, the output image was recorded on Kodak #5386 film. The film, after development by the Kodak processing laboratory, was then printed on TSC's Chromega enlarger using a neutral mix - 30 magenta, 30 cyan and 30 yellow. As a starting point for the laser mix, data from the Kodak spectral sensitivity curves for #5386 film were used: 1:2.2:7.0 for blue: green: red. Since these curves were derived for non-laser sources it was not expected that the initial results would achieve the proper color balance. This proved to be the case. The predicted light energy was found to be off by a factor of approximately 30: an energy level 30 times that predicted was found necessary to produce a reasonable exposure on the #5386 output film. After many "cut-and-try" experiments, a laser light mix was found which gave a relative good color balance on the output film in the absence of spatial filtering. At this point the final trimming of the color balance was done with the Chromega enlarger color balance controls. The laser mix required under these conditions was 1.0: 2.65: 4.0 for blue: green: red, with an exposure time of 0.5 seconds.* The results of defogging the laboratory fogged #5386 film will be presented in the following section. Anticipating the results, the defogging by spatial filtering of this film was very successful.

The next series of experiments was aimed at restoring the color balance of the Apollo film by spatial filtering in the coherent optical processor. Since the Apollo photography was done on a different type of film (Kodacolor) the required color balance of the laser light was different from that for the #5386 input film. As before, #5386 film was used to record the restored output image. The unfogged input used to properly set the laser light mix and Chromega light mix in the absence of spatial filtering was a test

* Absolute values of the light intensity incident on the input film: red- 2.35×10^{-5} watts/cm², green- 1.56×10^{-5} watts/cm², blue- 0.588×10^{-5} watts/cm².

target which had been photographed prior to the Apollo X flight and retained on ground. Fortunately, the original test target board was still in existence. This made it possible to compare the color balance of the output film with the original object. The same basic procedure of the previous experiments was used to set the color mix in the absence of spatial filtering. The Chromega enlarger mix was held constant at 30/30/30 while the mix of laser light in the optical processor was varied until the balance was close. The final adjustment was then made on the Chromega enlarger. The TSC photolab is equipped with a Kodak VCNA analyzer and Model I Translator, which greatly facilitated the final balancing. The final laser mix was 1.32: 2.12: 1.00 for the red, green and blue.* Each time the development chemistry is replaced or a new batch of printing paper is used, the balance must be changed slightly to preserve the color fidelity.

Unfortunately, before this project was finished we ran out of the Kodak #5386 film. Upon reordering, it was discovered that Kodak had discontinued making this film. They are now supplying #5038 as a replacement for #5386. A roll of #5038 was obtained and tried in the optical processor. A roll of #5386 was also obtained from NASA Houston just in case the #5038 was unsatisfactory. The #5038 did seem to be better in maintaining its color balance and also in speed. The latter consideration was becoming increasingly important, as the laser output was dropping off slightly with age. Consequently, some of the last Apollo pictures restored were recorded on #5038; the rest were on #5386 film.

The results of these two experiments, the restoration of the laboratory fogged film, and the naturally fogged Apollo film, will now be presented.

*Absolute values of light intensity incident on the input film: red- 182×10^{-5} watts/cm², green- 2.92×10^{-5} watts/cm², blue- 1.38×10^{-5} watts/cm², with exposure times of about 0.7 sec.

7. RESULTS

7.1 ARTIFICIALLY FOGGED IMAGERY

In order to gain an understanding of the basic process of de-fogging by optical spatial filtering it was decided to do a series of experiments using film imagery fogged in the laboratory with white light. A test target was prepared consisting of a standard Kodak color print ("Shirley"), a neutral density step tablet, the three basic colors (cyan, magenta and yellow) and a series of miscellaneous color swatches. A standard copying set-up was used to hold a 35 mm camera loaded with Kodak #5386 film. A series of frames was shot with controlled amounts of fogging. This was done using a double exposure technique. First an exposure was made of the test target. Then the test target was removed and a piece of white cardboard put in its place. A second exposure was then made for a fraction of the time of the original exposure. This fraction was chosen to be 3%, 6%, 12%, 25%, and 50% of the original exposure time. As expected, the prints from these frames showed a progressive loss of contrast and color balance. Figures 5 through 8 show the results of this progressive fogging. Figure 5 shows the target with no fogging. The fogged 35 mm slides were then placed in the coherent optical processor, and spatially filtered to see if some of the contrast and color balance could be restored. The best restoration was obtained with spatial filter (SF) #54. This filter has a peak attenuation on axis of 19%. The results of this are shown in Figure 9. When compared to Figure 7, the 25% fogged input frame, a definite restoration of the contrast and color balance is apparent. The restored output image of the optical processor was recorded on Kodak #5386 film. Both films were processed by Kodak and printed at TSC using the same mix in the color enlarger. This is necessary to insure a valid scientific comparison.

The optical transmission of the spatial filter for optimum restoration experimentally (81%) agrees reasonably well with Falconer's theory that it should match the degradation of transmission of the fogged film (73%) for the fogged film used for the input.

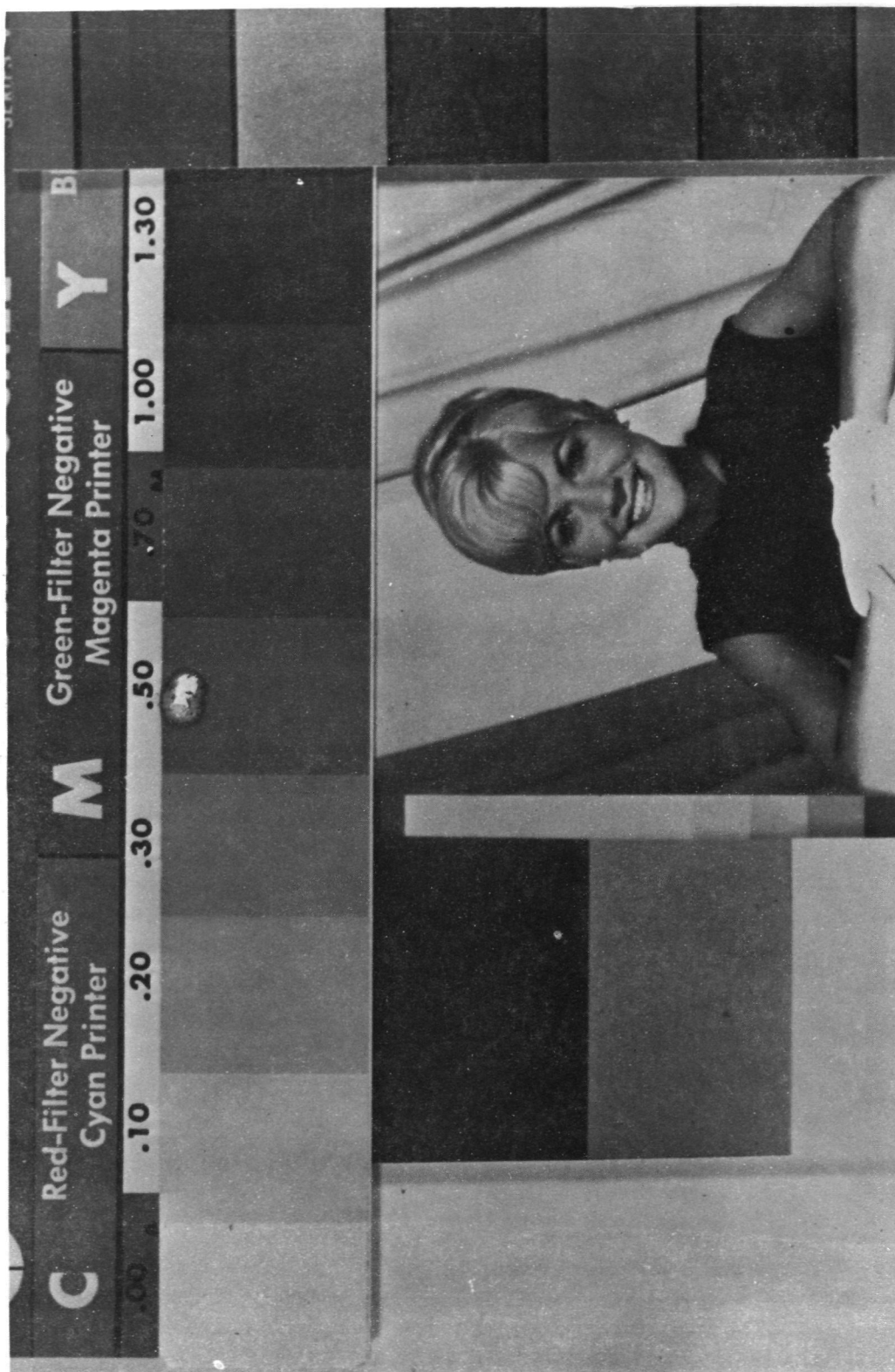


Figure 5. "Shirley" Test Target, Unfogged



Figure 6. 12.5% Fogged Test Target

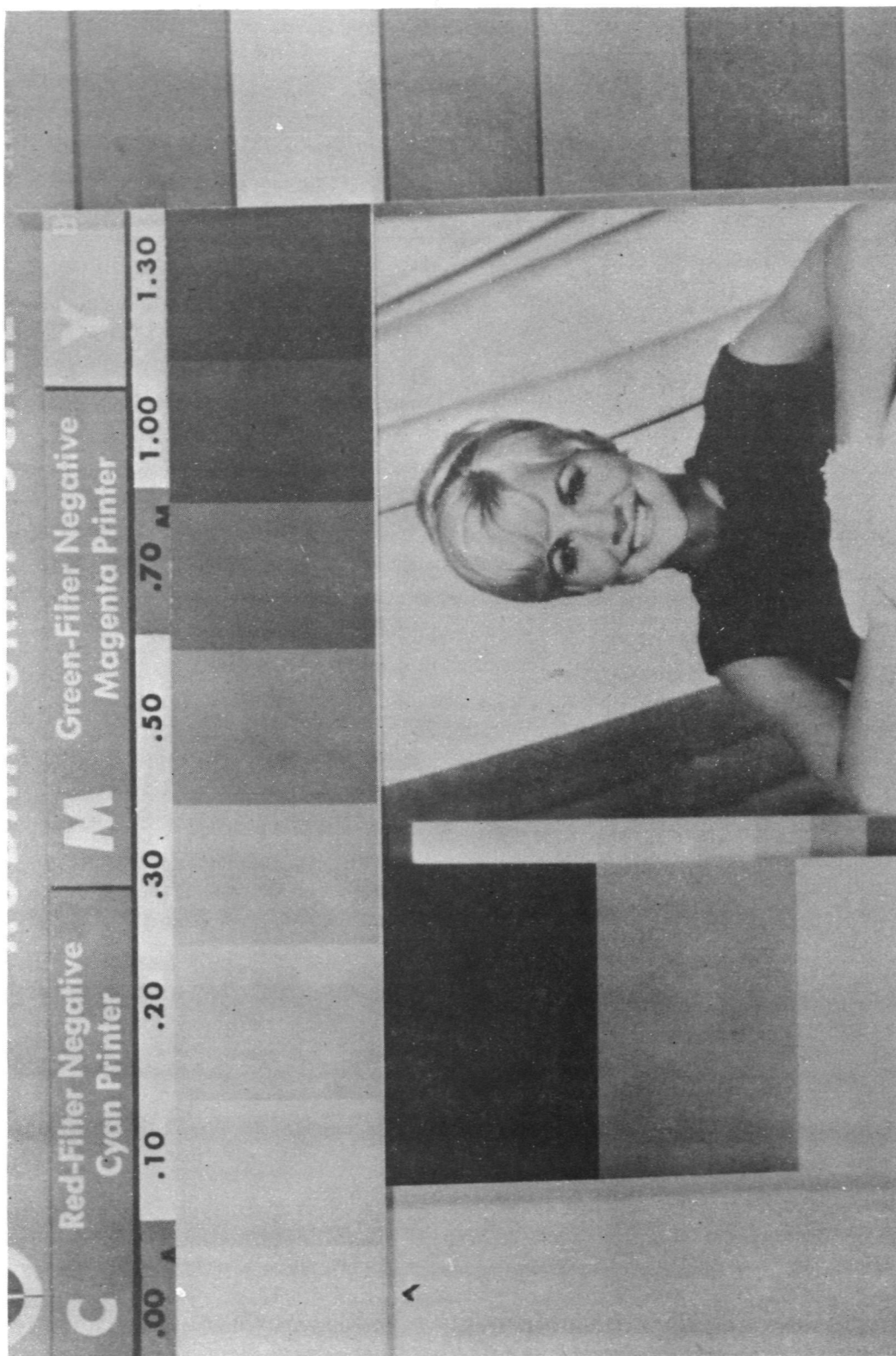


Figure 7. 25.0% Fogged Test Target



Figure 8. 50.0% Fogged Test Target



Figure 9. Defogged 25% Test Target

7.2 EXPERIMENTAL DEFOGGING OF APOLLO FILMS

Proceeding from the successful efforts in defogging the laboratory fogged imagery a similar series of experiments was undertaken using the films from the Apollo flight.

In preparation for a series of experiments on the effects of radiation fogging on film carried outside the Earth's protective atmosphere by astronauts, three magazines of Kodacolor film were assembled early in 1969. A test panel was constructed consisting of red, blue, yellow and gray panels, specimens of rock resembling the texture of rocks thought to be found on the moon, and a neutral density reflective step wedge. On Friday, April 25, 1969, the three magazines were flown over Holloman Air Base in New Mexico, and exposures of the above test panel were made with a Hasselblad electric camera at altitudes of 50,000 and 2,000 feet. Exposures were also made at ground level. Some of this film was developed the following week in order to determine the sensitometry and optimum printing parameters. On May 9, 1969, magazine I was transported to Cape Kennedy to be mounted at the appropriate time in one of the electrically operated 70 mm Hasselblad cameras used in photographing the moon's surface by the Apollo X astronauts. Magazine II was used as a control for latent imagery effects. No change in latent imagery was experienced, despite the fact that this film was exposed on April 25, 1969, and processed on May 28, 1969 - a lapse of 33 days.

The film from magazine I, exposed by the astronauts during the Apollo X flight, was returned to the MSC Photographic Technology Laboratory and processed on May 28, 1969. Densitometry on the several frames of magazine I exposed to the test target, when compared to the same frames on magazine III, showed an increase in base density ("fogging") which was attributed to the extra-terrestrial radiation to which the spacecraft was exposed. Mr. Reinbard of Eastman Kodak Company performed an experiment on Kodacolor film which showed that the same changes in base density

could be achieved by exposing the film to a radiation level of 0.75 RADS. It was the conclusion of Eastman that the radiation level may have been a bit higher than that indicated by the dosimeter readings -- possibly in the range of 0.65 to 0.75 RADS. Comparable experiments at MSC indicated similar conclusions. The densitometer indicated an increase of 0.15 in the red, 0.16 in the green and 0.18 D units in the blue.

A necessary condition for the successful application of defogging by coherent optical processing is to have a valid set of "before" and "after" films, where the only difference is the effect of radiation fogging. This is of utmost importance, because two things affect the final color balance in making prints from film restored in a coherent optical processor: 1) the mixture of the red, green and blue laser light in the processor, and 2) the mixture of the cyan, magenta, and yellow light in the color enlarger. These two factors must be determined for each different type of film used in the output of the coherent optical processor to record the defogged image. The "after" film, from magazine I, was deposited at this center in 1969. There is no problem identifying this roll, as the frames clearly could have been taken only from the vicinity of the moon.

The documentation of the "before" film unfortunately is not as certain. On May 10, 1974, Mr. Fred J. Southard turned over to the author the remaining film from the Apollo X flight. This consisted of 13 70 mm strips, each containing 4 frames apiece of the test board target. The two pages of documentation furnished did not unambiguously confirm that this film represented a "before" case -- i.e., a picture of the test board which was not taken aboard Apollo X and hence fogged. Stated another way, we can not be absolutely sure that these strips were from magazine II or III, and not from I.

In the absence of any viable alternative, the assumption was made that these strips were a "before" case, and experiments with defogging the Apollo film were started. The first step was to balance our color processes. A properly exposed frame of the

"before" color film was placed in the input of the coherent optical processor and type #5386 in the output plane. A series of experiments was undertaken to determine the proper laser and color enlarger mixture of intensities to reproduce faithfully the colors of the test target board. This board was kept at TSC, so that an actual comparison could be made. The #5386 was sent to a Kodak Processing Laboratory in Fair Lawn, New Jersey for processing, to insure repeatability. All this was done with no spatial filter present in the coherent optical processor. Unfortunately, the above set of tests had to be repeated in the middle of the restoration experiment because Kodak had stopped manufacturing #5386, replacing it with #5036 which they claimed was superior.

The results of spatial filtering the Apollo X film are presented below in two groups. One group is the experiments in defogging the test target; the other is the experiment in defogging the picture of the moonscape.

Figure 10 shows what is believed to be the unfogged test target from either magazine II or III. It is this frame that was used to balance the laser light and Chromega enlarger light mix, as described above. The next figure shows the results of spatial filtering the fogged test target frame (from magazine I); Figure 11 is with filter #54; Figure 12, filter #56; and Figure 13, filter #57. Figure 14 shows the fogged test target with no spatial filtering. The following table gives the optical properties of the above spatial filters.

Filter #	Peak Density (% Transmission)	Half-Intensity Width (Microns)
36	81	30.5
54	81	76.0
56	75	76.0
57	64	71.0

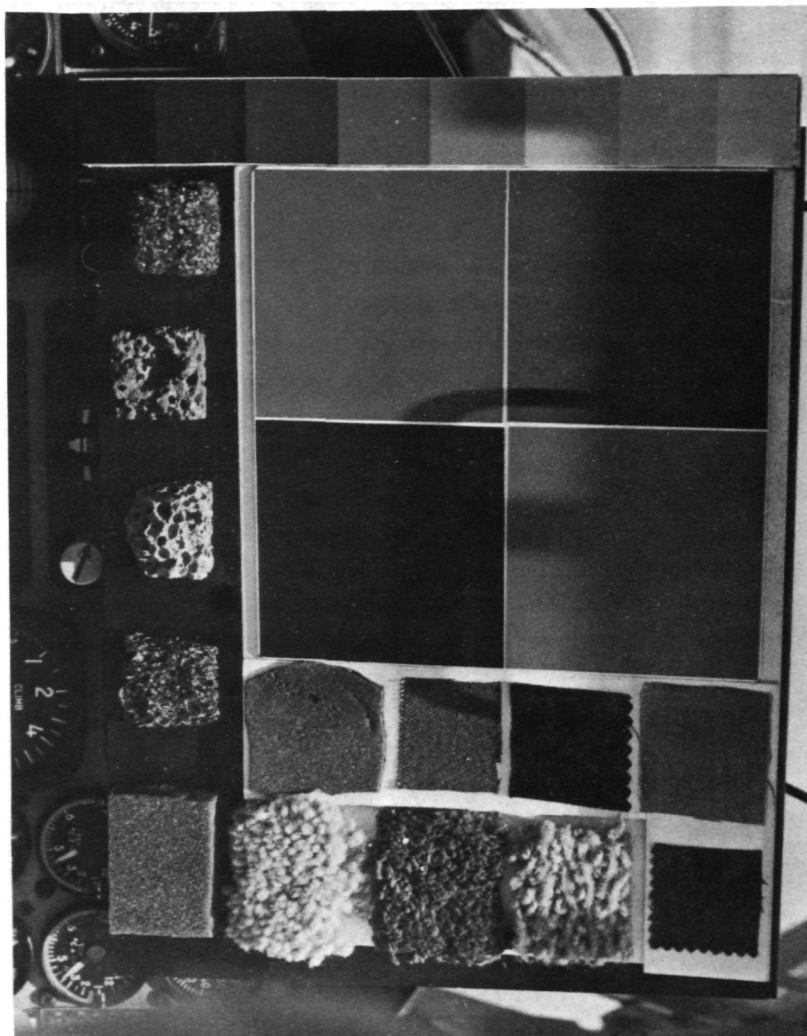


Figure 10. Unfogged Apollo X Test Target

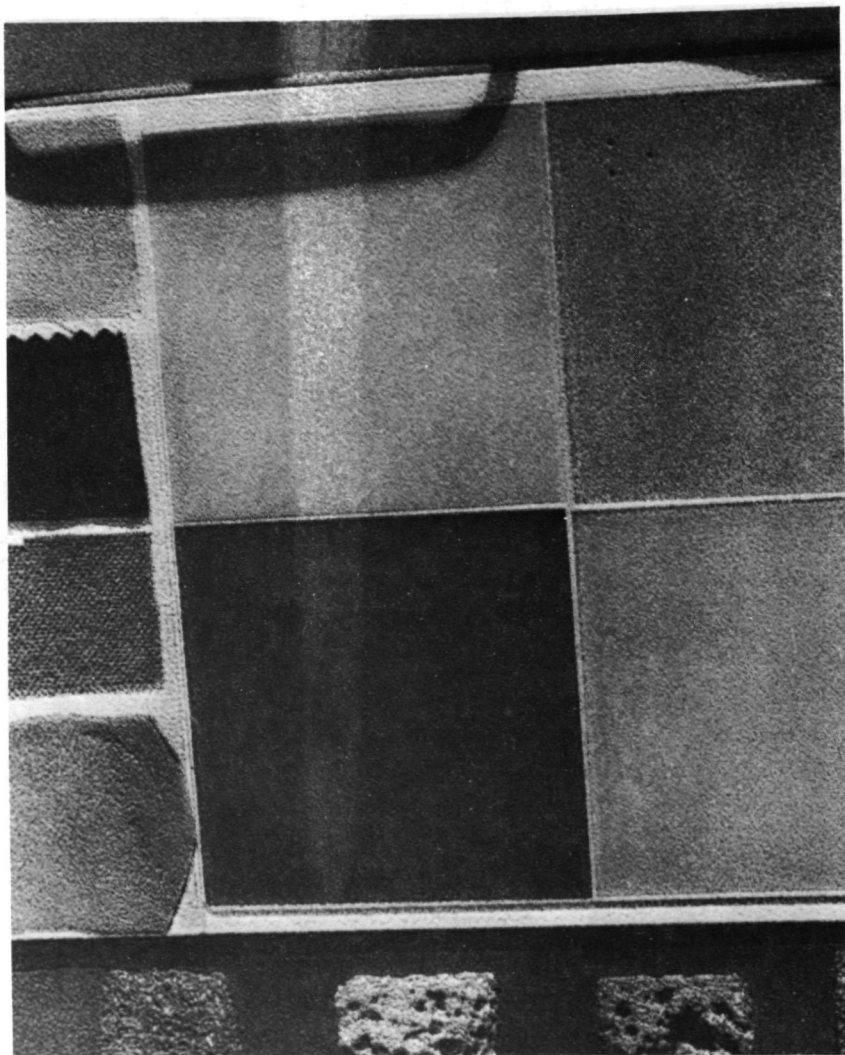


Figure 11. Fogged Test Target Input, Defogged with Spatial Filter #54

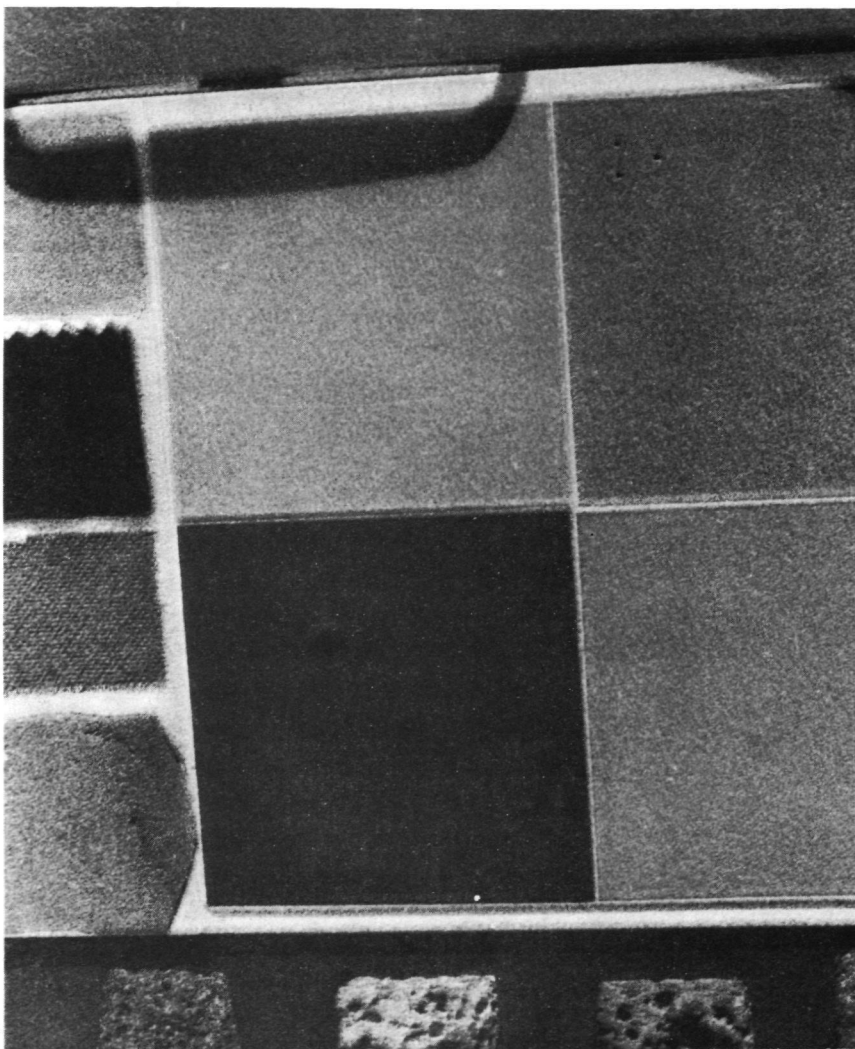


Figure 12. Fogged Test Target Input, Defogged with Spatial Filter #56

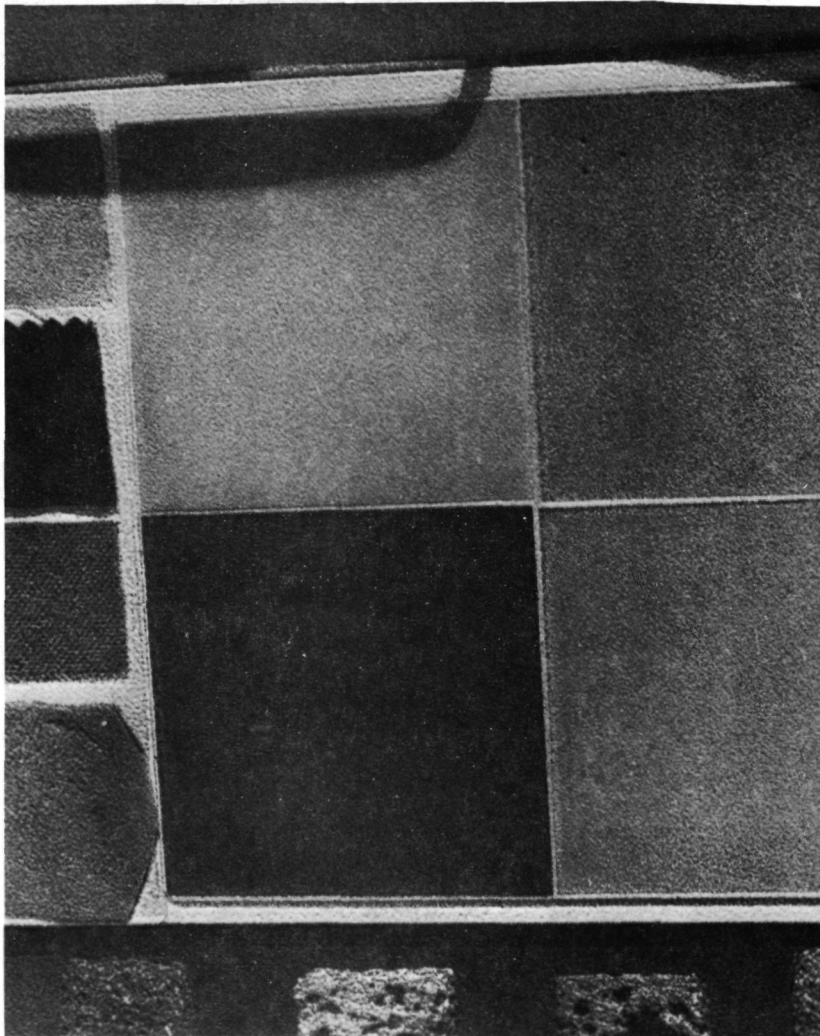


Figure 13. Fogged Test Target Input, Defogged with Spatial Filter #57

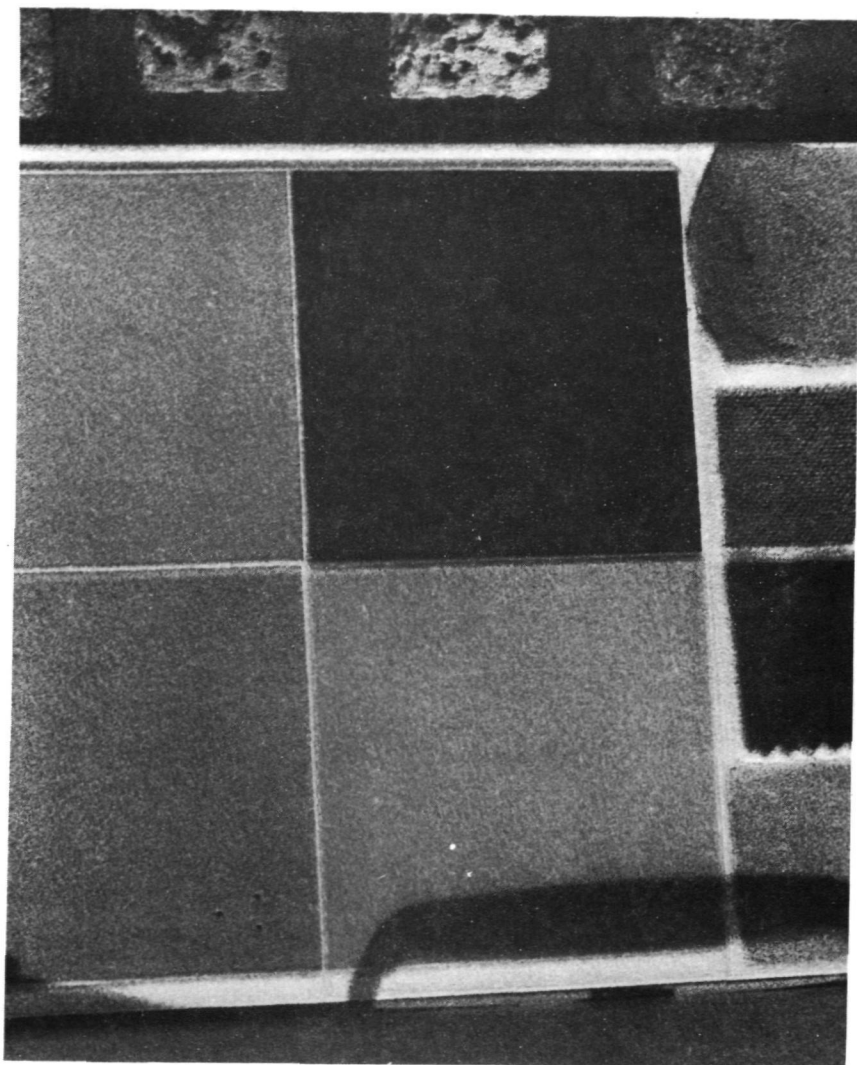


Figure 14. Fogged Test Target Input, No Spatial Filter

Figures 15 through 19 show the results of spatial filtering one of the frames of the moonscape (Part 2, frame 3 of the original Apollo film); Figure 15 is spatial filter #54; Figure 16, filter 56; Figure 17, filter 57; Figure 18, filter 36; and Figure 19, no spatial filter.

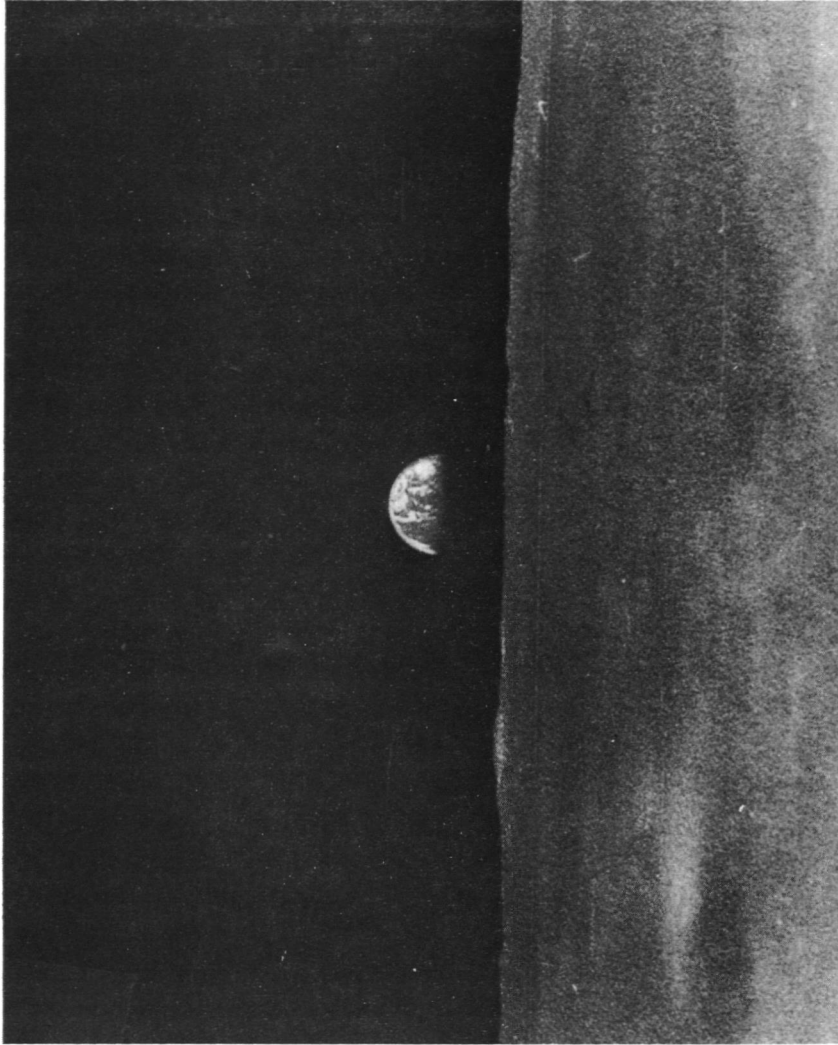


Figure 15. Apollo X Mooncape, Defogged With Spatial Filter #54

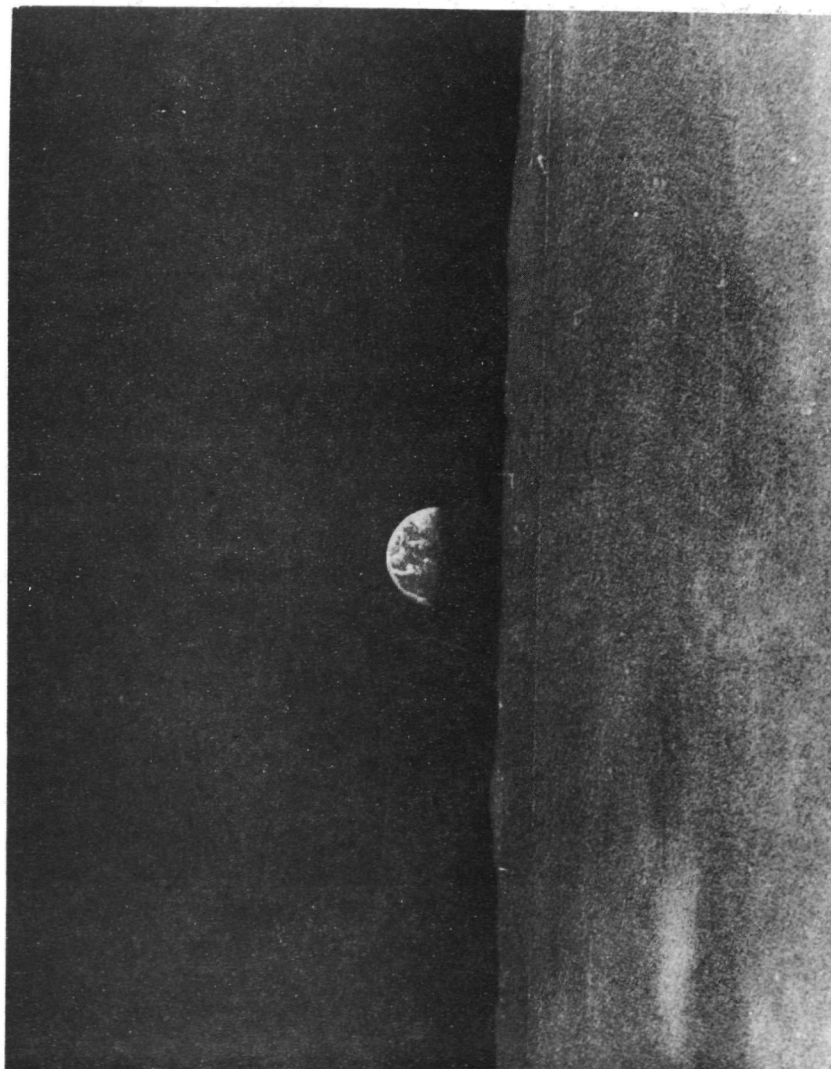


Figure 16. Apollo X Mooncape, Defogged With Spatial Filter #56

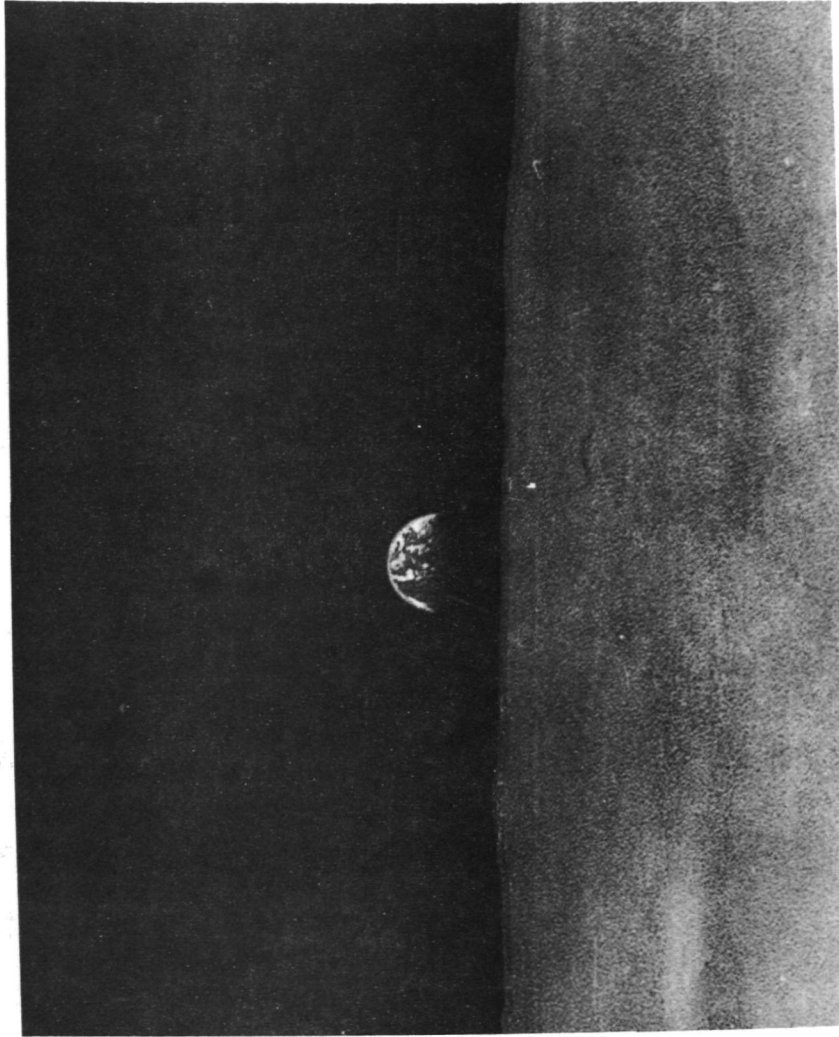


Figure 17. Apollo X Mooncape, Defogged With Spatial Filter #57

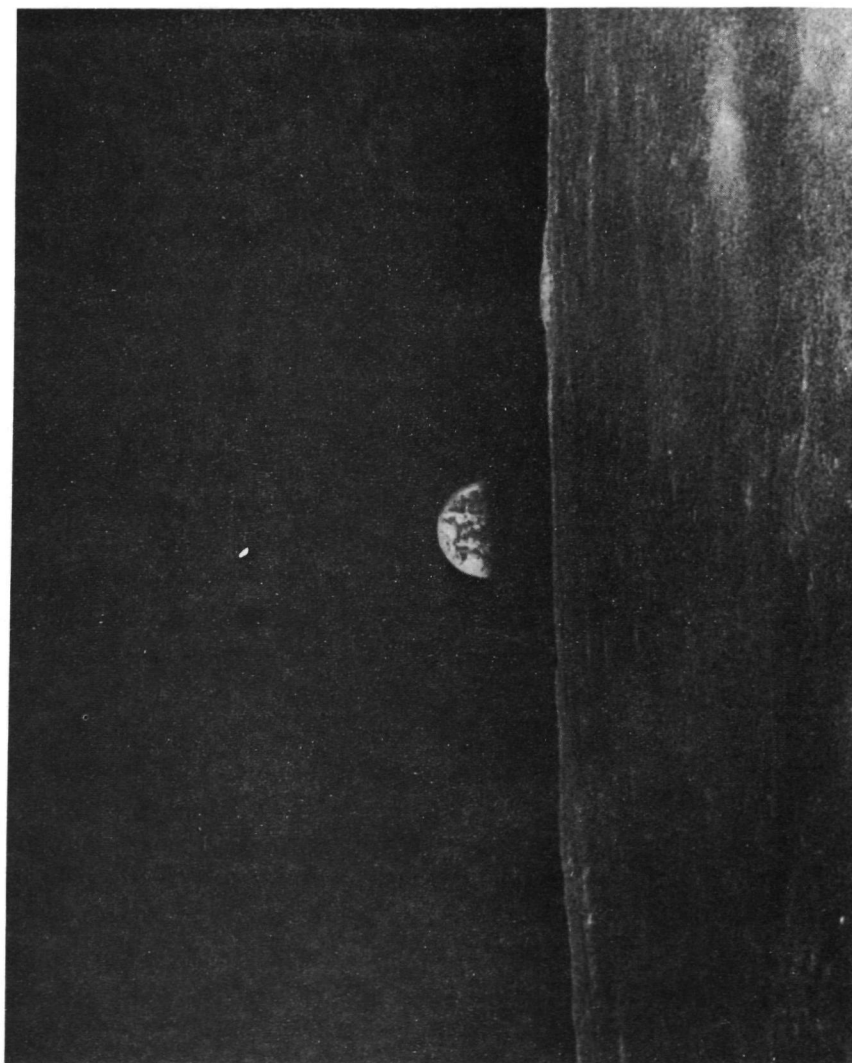


Figure 18. Apollo X Moonscape, Defogged With Spatial Filter #36

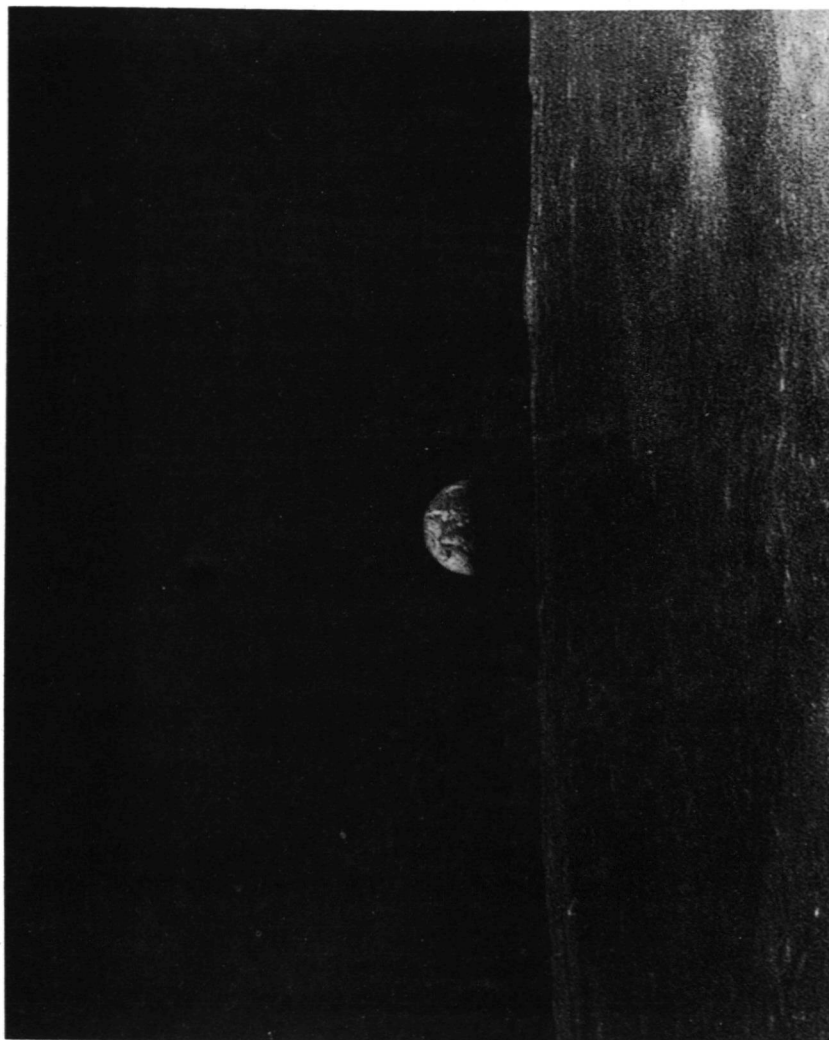


Figure 19. Apollo X Moonscape, No Spatial Filter

8. CONCLUSIONS

In examining the result of the defogging attempts by spatial filtering we conclude that the process worked in the case of the laboratory fogged film; both color balance and contrast were enhanced. In the case of the Apollo film, there was no significant difference between the various spatially filters. Hence it must be concluded that the technique was not successful with the Apollo film.

Although one can not say definitely why this is so, several possible reasons are suggested. In the case of the laboratory fogged film, everything was under the control of one person, and there was no uncertainty as to the identification of the very necessary calibration frame. In the case of the Apollo film, by the time the control magazine was acquired by TSC, some five-and-a-half years after it was shot, the documentation was fragmentary. Unfortunately, a search of the TSC files on this project failed to turn up any duplicate documentation. Although we believe that the frame taken to be a calibration shot of the test target was just that, we can not be absolutely certain of this.

Another significant difference in the two experiments was the film used. The laboratory fogged frames were made using Ektachrome (#5386 and #5038); the Apollo film was made on Kodacolor. Kodacolor is a negative film containing an orange-tinted base, so that prints can be obtained directly. Ektachrome, a positive film, does not contain this orange base, which was the reason for using it in the first place; with it in the output of the coherent optical processor, and the Apollo film in the input, the requisite orange mask would automatically be incorporated into the spatially filtered frames and color prints could be made directly. Possibly the coherent optical processor can not handle the orange base for some reason.

Another possible reason might be in the age of the Apollo film. Five-and-a-half years lapsed between exposure and these defogging experiments. Some slow acting chemical degradation pro-

cess could have been taken place which additionally altered the color balance. The correct explanation could be one, or a combination of all of the above reasons.

The laboratory fogged films show that the coherent spatial filtering method can successfully defog photographic color film under controlled conditions. Future work should be done with contemporary film under tightly controlled conditions.

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APPENDIX
COHERENT OPTICAL NOISE SUPPRESSION
DEVICE

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Coherent Optical Noise Suppression Device

Joseph L. Horner

In optical data processing the quality of the output image is usually degraded by diffraction noise generated by the optical components of the system. The suitability of previously suggested techniques to a dc spatial filtering processor is discussed. A new system is proposed that overcomes the problems of the previous noise suppression techniques. Experimental results of the new system are presented along with a determination of the resolution of the system. The errors and limits of the new coherent noise suppression system are discussed.

Introduction

Like holography, the field of optical data processing has enjoyed a renaissance with the advent of the laser. The results of image enhancement by spatial filtering are frequently marred by the coherent optical noise generated by the optical components of the optical processor itself. The highest quality lenses and flats, when illuminated with laser light, show a random collection of bull's eye patterns, wavy lines, and ripples. One source of this clutter is the volume imperfections in the glass—bubbles, dirt or dust particles, inclusions, and striae. Even with perfect glass, there would still be an optical noise problem due to reflections from the air-glass interface of the lens elements and due to the fact that the grinding and polishing operations apparently produce microfissures on the glass surface, as shown clearly by the work of Thomas.¹

Antireflection (AR) coatings can be applied to each lens element and eliminate their reflections in systems that work at a single laser wavelength. However, in the present project the input film is color film that requires red, green, and blue laser light. It is not possible to get AR coatings that are 100% effective over this wide a band of wavelengths.

Several techniques and devices have been proposed for suppressing this optical noise. However, before discussing these, it is necessary to explain the spatial filtering problem for which the present coherent optical processor was built and why the existing techniques were inappropriate. During the NASA Apollo series of moon explorations, it was discovered that the color film taken aboard was fogged by space radiation when the protective shield of the earth's at-

mosphere was absent. The present series of experiments was undertaken to see if the techniques of coherent optical spatial filtering could be used to defog this film and in particular to restore the color balance degraded by the fogging process. Generally the results have been successful, and a full report of this work will be published at the conclusion of this contract.² Defogging a film is accomplished by readjusting the proper balance of the dc and ac spatial frequencies. This requires a dc spot filter in the Fourier transform plane of the optical processor. The spot filter is a gray dot, typically several tens of microns in extent, placed exactly on the optical axis.

Prior Noise Averaging Techniques

Thomas¹ suggested placing a tilted optical flat in the collimated laser beam. During the exposure of the output film, the flat is rotated about the optical axis. This causes the origin of the axes of each noise pattern to rotate while the desired image remains stationary, thus tending to average out the noise. The rotating flat also causes the Fourier spectrum incident on the spatial filter to rotate in a similar fashion. To keep the spatial filter in alignment with the moving spectrum, he proposes an optomechanical feedback system (transform tracker) to make the filter move in synchronism. In some spatial filtering problems, where the physical size of the active part of the spatial filter is large compared to the rotation of the spectrum, this problem can be neglected altogether, e.g., the work on enhancing atmospheric turbulence degraded film³ where the spatial filter was about 5 mm across. However, in the problem of dc filtering, where the filter is about 30 μm wide and alignment of about 5 μm is required, a tracking system to follow this would indeed be a challenging design problem.

Another system proposed by Grebowsky *et al.*⁴ used a rotating lens. This, like Thomas's approach,

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causes the noise pattern generated by the lens to rotate while the desired image (hopefully) remains stationary. The word *hopeful* is used, because the axis of rotation must exactly coincide with the optical axis of the lens, otherwise the image also moves. For a single element lens this is possible to achieve. However, in a multiple element lens system, there will always be some misalignment of the axes of the individual elements. Each Fourier transform lens in the present processor consists of eight elements. In addition, a separate rotating device would have to be built for each lens assembly, adding to the cost, complexity, and alignment problems using this approach.

In a patent (3,729,252), Nelson proposes using a multiplicity of n sources, each producing a displaced pattern of the noise in the output plane of the processor, while producing n desired images in registration. The problem here, like Thomas's system, occurs in the spatial filter plane; there are n individual, displaced, possibly overlapping, Fourier spectra. This overlap for dc spatial filtering would not be a problem, but it is now about n times as difficult to fabricate the spatial filter. To apply this scheme to the present optical processor, with its three different colored lasers, keeping in mind that each source must be lined up with its own spatial filter in the Fourier transform plane, seemed like a formidable task.

Present System

Fortunately, an idea for a simple noise averaging scheme occurred to us, one which obviates all the problems and disadvantages of adapting any of the other known systems to the particularly spatial filtering problem at hand. The scheme is shown in Fig. 1 and is based on the simple principle of moving the input and output film planes together during the exposure; the noise pattern remains stationary while the desired (filtered) image moves through it. The upper portion of the figure shows the standard afocal coherent optical spatial filtering system, and the lower portion is the noise suppression system. The

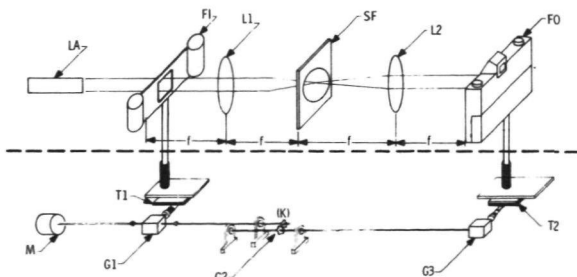


Fig. 1. Afocal coherent optical data processor (upper half of diagram) consisting of laser LA , input film FI , first Fourier transform lens $L1$, spatial filter SF , second Fourier transform lens $L2$, and output film FO . Lower portion of diagram is coherent optical noise suppressor consisting of drive motor M , right-angle gear box $G1$, reversing gear assembly $G2$, right-angle gear drive $G3$, and micrometer adjusting translation tables $T1$ and $T2$.

afocal system has an over-all image magnification of unity. The driving motor M links to a right-angle gear drive $G1$ that turns the micrometer advancing the translation table $T1$ holding the input film. A linkage connects the gear drive to a reversing gear train $G2$, since it is necessary to drive the input and output films in opposite directions. If the over-all magnifications of the optical processor is some other value K , the reversing gear train $G2$ would also have to have this ratio, assuming $G1$ and $G3$ are identical. Another right-angle gear box $G3$ drives the micrometer advancing the translation table $T2$ (identical to $T1$) which holds the output film. An electronic timing chassis controls the motor and a solenoid actuated shutter. The timing chassis opens the shutter after the motor gets up to speed (1600 rpm), closes the shutter after the proper exposure time (set by a potentiometer on the front panel), then reverses the motor without opening the shutter, bringing the input and output films back to their original positions (to within about 0.2 mm). The total travel for a 1/2-sec exposure is 4 mm.

Results

If there were no backlash in the gears, no flexure in the linkages, and the magnification of the optical system were exactly unity, there would be no adverse effects on the resolution of the optical system when the noise averaging system is operative. Of course, none of these conditions are exactly true. To measure this degradation on the performance, a Sayce target containing fundamental spatial frequencies from 5 lines/mm to 100 lines/mm was used as the input signal. The output was photographed on Pan-X 35-mm film with and without the noise suppression system operative. The 530.9-nm output (green) from a Krypton laser illuminated the film. Figure 2(A) shows the results of a microdensitometer scan of the exposed output film without noise suppression, while Fig. 2(B) shows the same thing with the noise suppression system operative. Without noise averaging the resolution is good to about 80 lines/mm, with noise averaging to about 35 lines/mm.

Error Analysis

Because of the nature of the output scan [Fig. 2(B)], it is concluded that errors in the mechanical parts of the system, i.e., the gears and linkages, are responsible for the upper limit of resolution. If the optical magnification of the system does not exactly match the gear ratio of the noise suppressor, after a travel length of L the input image will be out of registration with the output film by an amount L . This is equivalent to the well-known linear smear problem^{5,6} resulting in an output image Fourier spectrum,

$$I_{OUT}(\nu) = I_{IN}(\nu) \cdot \text{Sinc}(\pi\nu\Delta L), \quad (1)$$

where Sinc is the familiar $(\sin x)/x$ function, and ν refers to the spatial frequency. Since we do not observe a Sinc function modulating the spectrum of Fig. 2(B), we conclude that this is not the problem. A measurement of the magnification, made from the

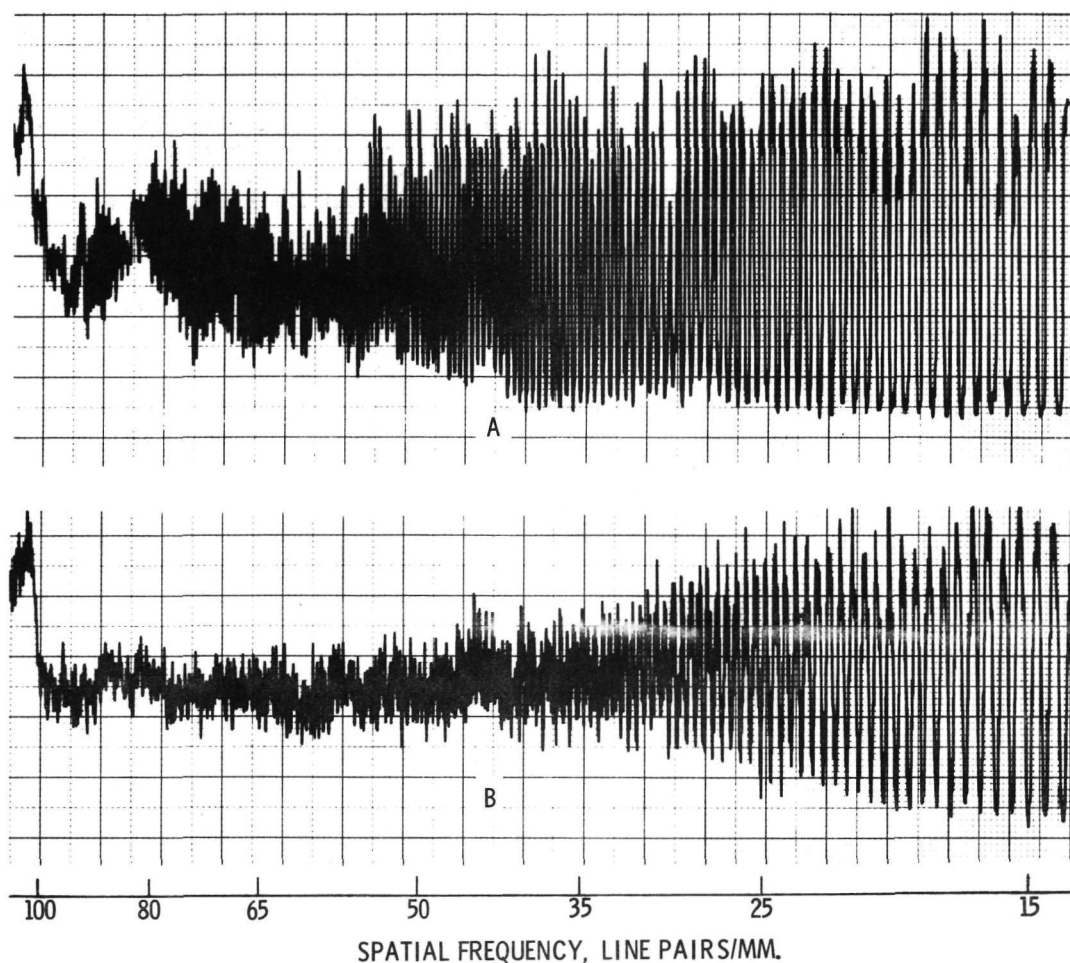


Fig. 2. (A) Microdensitometer scan of output film image, 15–100 lines/mm. Sayce target, without optical noise suppression device operative. (B) Same as (A), but with optical noise suppression operative.

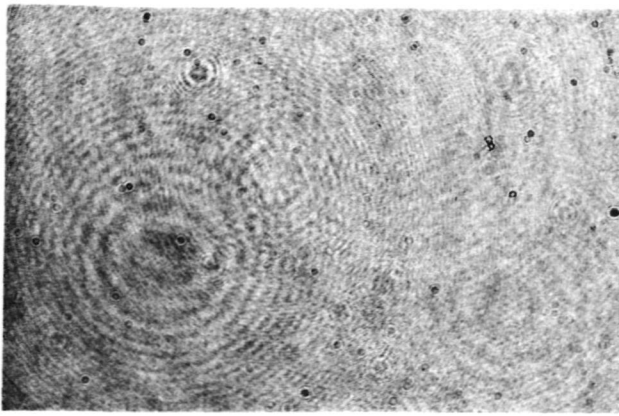
Sayce target, gives a value of $1.00352 \pm 20\%$, which would place the first zero of the Sinc function of Eq. (1) at

$$\nu_0 = 1/\Delta L = 1/[L(K - 1)] = 56.8 \text{ lines/mm.} \quad (2)$$

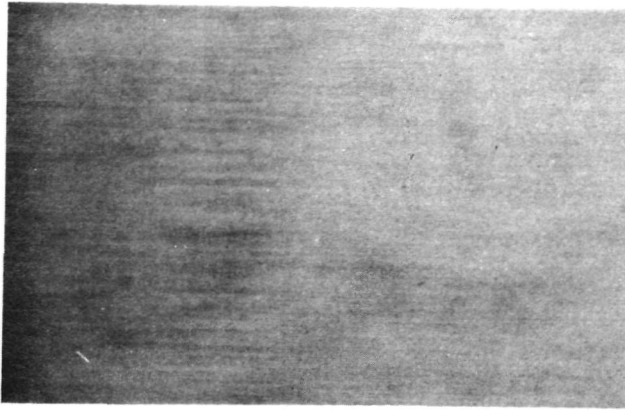
This is well beyond the observed cutoff at 35 lines/mm. Fortunately, for the problem at hand, 35 lines/mm is well beyond the resolution required for processing the desired imagery (typically photographs of the moonscape and earthrise).

Figures 3(A) and (B) show the effectiveness of this

noise average technique. Figure 3(A) shows the noise in the output plane with no input present and no noise averaging and Fig. 3(B) with the noise suppression device operative. In all fairness to the lens manufacturer⁷ it should be pointed out that the clutter shown in Fig. 3 is worse than actual; an accumulation of dust was allowed to gather for a few days to show the effectiveness of the noise averaging system. The lenses are of the highest cosmetic quality this author has experienced. A photograph of the system is shown in Fig. 4.



A



B

Fig. 3. (A) Output film picture of processor with no input film present, showing coherent optical noise generated by processor, without noise suppression device operative. (B) Same as (A), but with optical noise suppression device operative.

Conclusions

A device to suppress coherent optical noise is presented with the following properties:

(1) It averages all the noise, with a single device, generated by all optical elements between input and output film planes, as well as noise generated before the input film, e.g., the collimation lens.

(2) It can be easily added to any existing optical processor without any modifications to the existing processor.

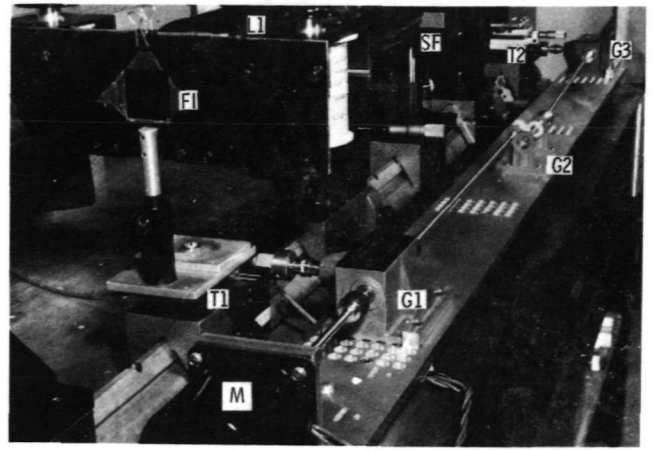


Fig. 4. Optical processor (upper portion of photograph) with optical noise suppression device (lower portion of photograph). Labels same as Fig. 1.

(3) The Fourier transform pattern remains stationary and unitary.

(4) It is simple and inexpensive to fabricate from off-the-shelf components.

(5) It does not require critical or difficult alignment.

(6) Any desired degree of noise suppression can be achieved by simply controlling the motor speed or exposure time.

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